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Stair Climbing Robots and High-grip Crawler

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1. Introduction

Stair climbing is one of the most attractive performance of mobile robot for both legged and wheeled. (e.g. Stoeter et al., 2002; Murphy, 2000; Yim et al., 2000; Krishna et al., 1997; Granosik et al., 2005; Liu et al., 2005; Arai et al., 2006; Tanaka et al., 2006; Miyanaka et al., 2007; Tsukagoshi et al.,2005)
Authors have been developing various kinds of stair climbers, considering how to make its climbing ability higher and its mechanical complexity reasonable and practical. The research includes realizing a large step negotiating height, controlling to keep its centre of gravity almost the centre of ground contacting area, higher speed of climbing up, large load tolerance to carry on. Reducing body weight and energy consumption is also the important matter of developing.
In the first part of this chapter, we introduce some solutions to realize stair climbing machines that we developed. Each of them has good performance as in a category of their kind, e.g. various numbers of legged and wheeled shapes. Then, we discuss a development of high-grip crawler, which we think one of the best solutions as the stair climber.

2. Various Stair Climbers

2.1 Biped

We have been developing biped configuration robot named "YANBO" since 1985.
YANBO-1, as shown in Figure 1, was the first developed model (Yoneda, 1987). YANBO-1 consists of five Degrees of Freedom (DOF) which can be considered almost minimum DOF necessity for walking on the level ground. YANBO-1 is confirmed that by walking on horizontal level ground and climb stairs.
YANBO-2 (Ota et al., 2001a; Ota et al., 2002), as shown in Figure 2, and YANBO-3 (Ota et al., 2003), as shown in Figure 3, were second model which could be performed not only mobility but also manipulability to attach two more DOF. Additional DOF is allocated to each ankle joint and can help to generate three ankle joint motions freely. This helps to walk on incline slopes and appropriate manipulate motions. Then total DOF increases to eight, however, the number of actuators are still much less than other biped structure robot, like humanoid (Yoneda & Ota, 2003).

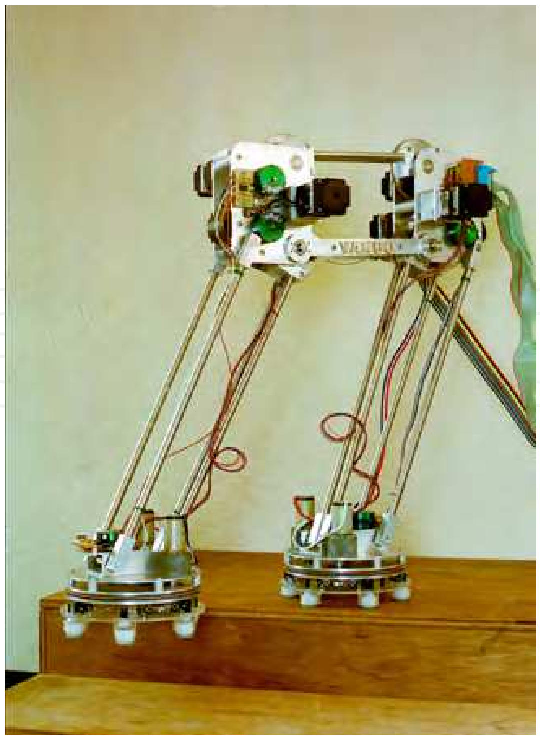


Fig. 1. YANBO-1, Stair climbing motion

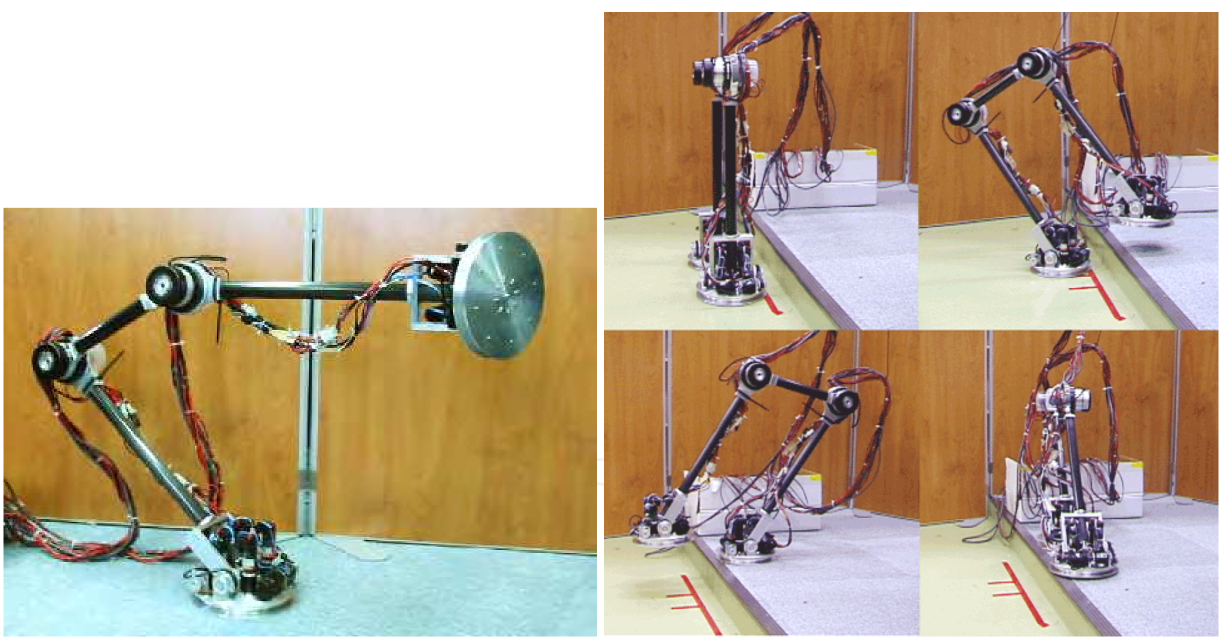


Fig. 2. YANBO-2, Step climbing motion.

2.2 Quadruped

Authors also have been developing various kinds of quadruped walking robot (Hirose et al. 2009). TITAN-VI, as shown in Figure 5, has succeeded to walk on stairs (Hirose et al. 1995; Yoneda et al., 2000). TITAN-VI consists of two separated body segments, where front and rear segment can slide linearly up and down in order to negotiate a large height difference of front and rear landing points on the stairs.

Fig. 3. YANBO-3, which also equipped with manipulability

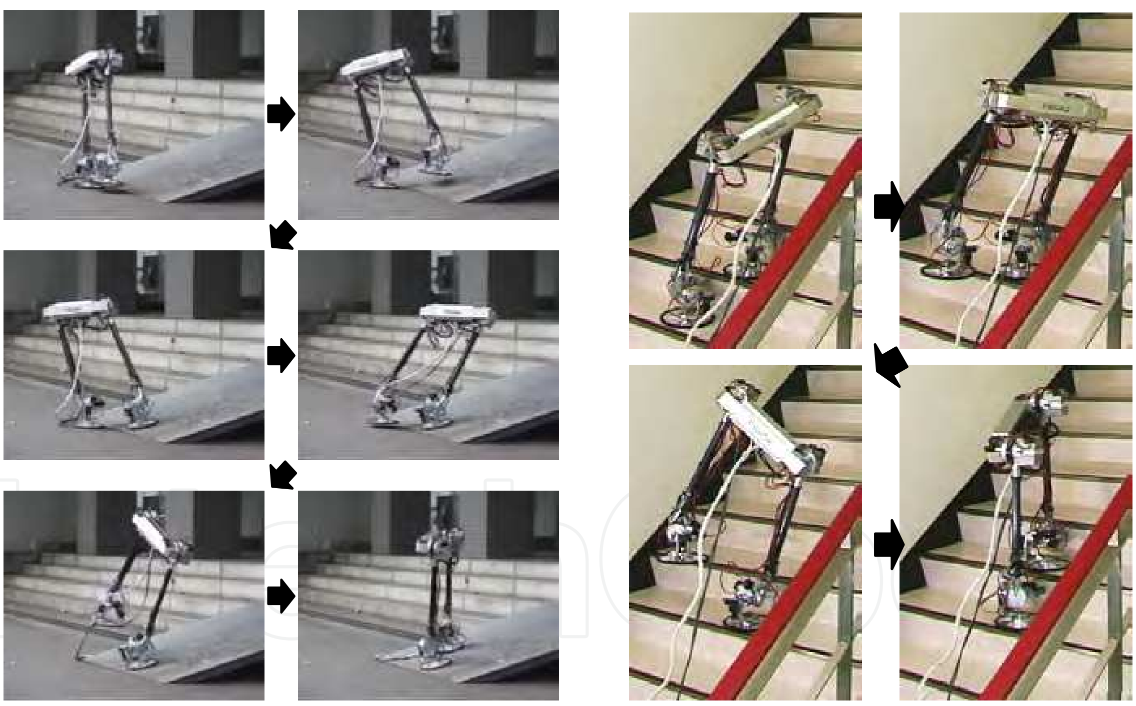


Fig. 4. Slope climbing (left) and Stair climbing (right) of YANBO-3

Authors have also been developed quadruped with another strategy, according to the design concept in which total number of actuators can be used as small as possible. Hyperion, as shown in Figure 6, was quadruped walking robot with minimum actuated-DOF for walking motion. (Yoneda et al., 2001a; Yoneda & Ota, 2003; Yoneda, 2007) Taking lightweight advantages with small number of actuators that is three motors are used in Hypeion-1 and 5 motors are used in Hyperion-2, a wall climbing robot “Hyperion-1SP” and “Hyperion-2SP” was developed. Wall climbing motion and ceiling walking motion of

Hyperion-1SP are shown in Figure 7 and Figure 8, respectively (Yoneda et al., 2001b; Ota et al., 2006). In Hyperion 2SP, transfer motion from ground to wall can be succeeded.

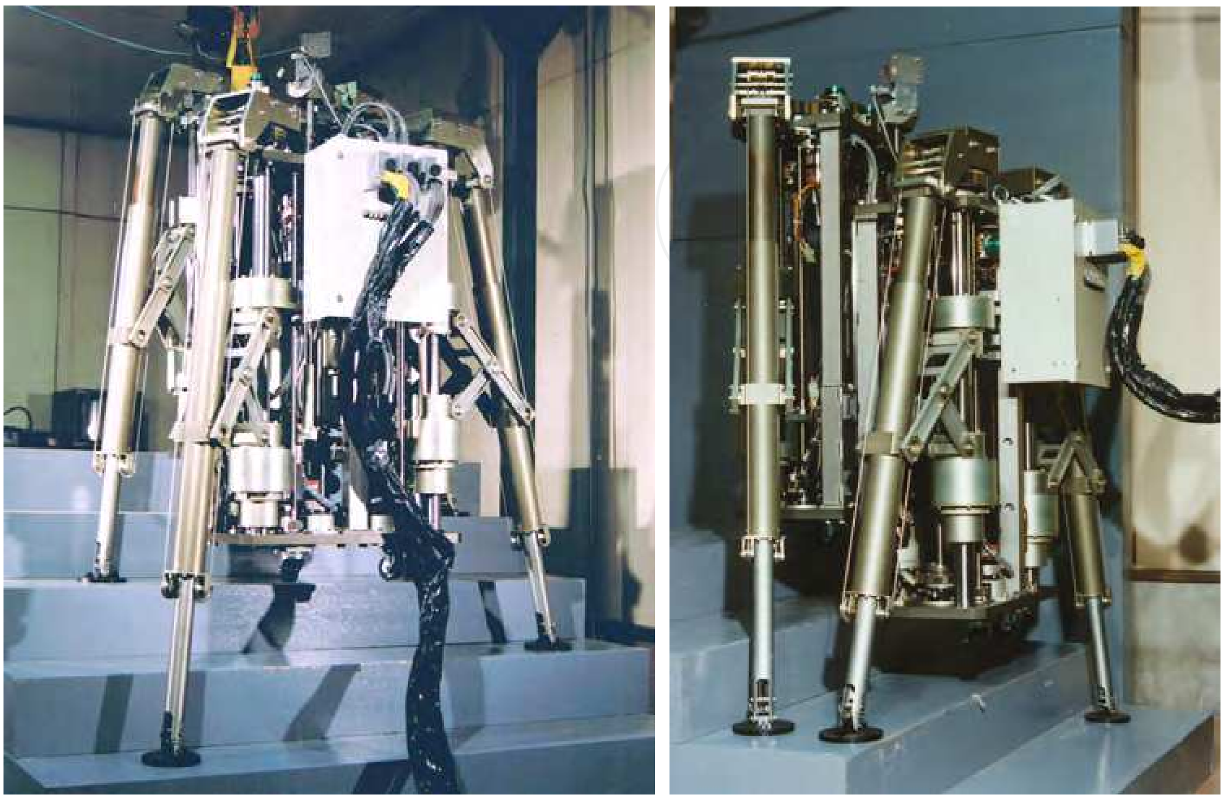


Fig. 5. TITAN-VI, Stair climbing motion, and two body segments can slide (right)

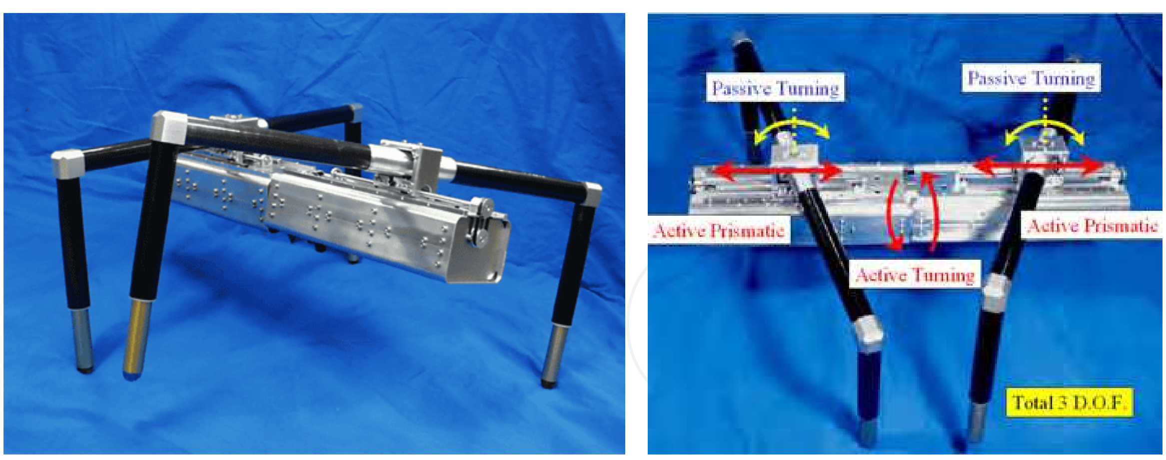


Fig. 6. Hyperion-1, and its DOF configuration

Fig. 7. Hyperion-1SP, light weight wall climbing robot

Fig. 8. Hyperion-1SP can succeed to walk on ceiling using blower and suction feet

2.3 Six-legged

We have been also developing six-legged walking robot. ParaWalker-II (Ota et al., 2001a;Yoneda & Ota, 2003), as shown in Figure 9, composed two frames with three legs each, and each frames are connected by three arms with two actuated joints. Total numbers of actuators are six to generate each frame 6-DOF motion that is necessary and sufficient DOF to lead walking and tasking motion. Moreover, in order to acquire higher step adaptabilities to move stairs, one more actuator was attached for extending a leg and keeping frame balance during stair climbing.

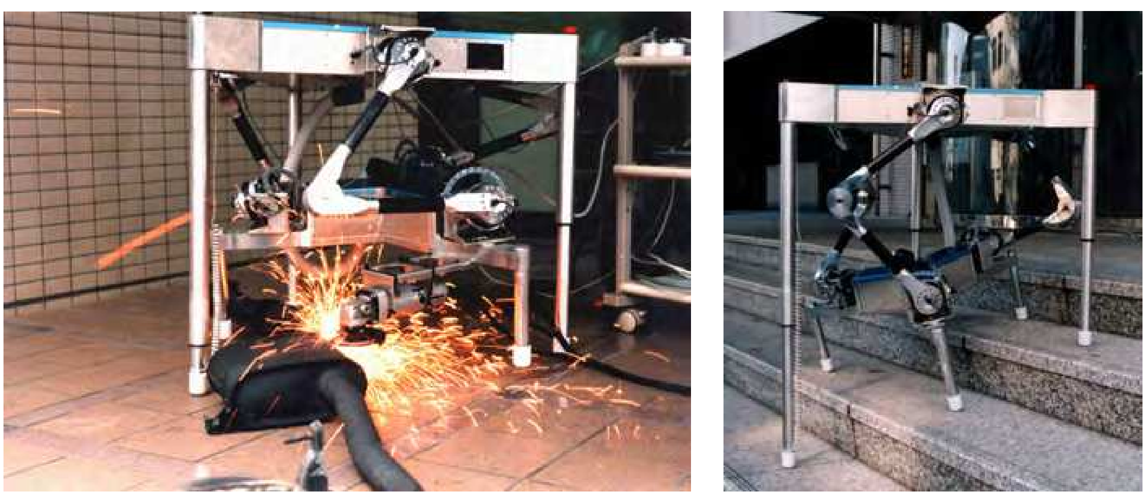


Fig. 9. ParaWalker-II, walking and task performing twin-frame mobile system, and its stair climbing motion to extend one leg

2.4 Leg-wheel Hybrid

Generally, legged-locomotion has very high adaptabilities. However, mobility of wheeled locomotion is much more interesting than legged-locomotion if the moving place is limited to a flat plane. Therefore, much higher mobility can be obtained if both methods are adopted; wheeled locomotion on flat planes and legged-locomotion on uneven terrain. We have developed several leg-wheel hybrid robots.

Hyperion-W has developed one of leg-wheel hybrid robot (Takahashi et al., 2006), whose base body is used the Hyperion-1, which is a quadruped robot with minimum three actuators mentioned above, and actuated wheels are attached to each legs. Hyperion-W can perform a hybrid motion of walking and running on uneven terrain as shown in Figure 10 and show its high mobility.

And we have another maneuver to realize the leg-wheel hybrid locomotion. YANBO-2 and YANBO-3, mentioned above, have 3-DOF ankle joint with eternity rotatable circle shaped sole. Therefore using these characteristics, both YANBO-2 and YANBO-3 can establish leg and wheel hybrid locomotion manoeuvres (Ota et al., 2002; Ota et al., 2003), as shown in Figure 11.

Fig. 10. Hyperion-W, a leg-wheel Hybrid robot

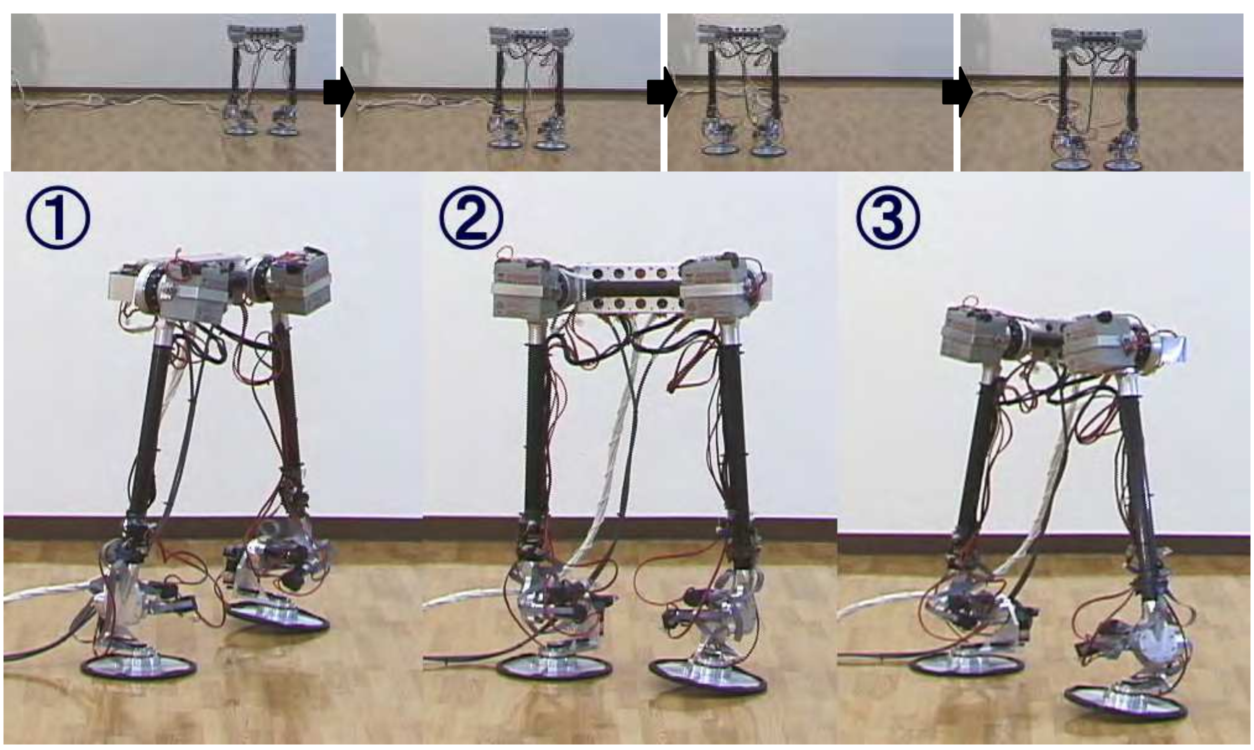


Fig. 11. Two different style of Leg-Wheel Hybrid locomotion in YANBO-3, wheeled locomotion (upper) and wheeled and leg mixture locomotion (lower)

3. Advantages of Crawler type Vehicles in practical use

Through from above mentioned various types of researches, we believe one of the realistic solution which the robots should support and help human tasks in our daily lives is to carry heavy baggage especially by wheeled or crawler type climbers. Because wheeled or crawler type vehicles have much more payload capacity than legged-walking robots have. Therefore, when carrying heavy objects, a cart is useful only on flat ground, and the load must be carried up or down stairs by hand. Conventional approaches to transporting heavy loads on the stairs have yet to be developed. Moreover, humans themselves sometimes require assistance in traversing stairs. Mobile robots require the ability to move with versatility, smoothly and with high efficiency in various environments. Robots with high mobility can easily be used in rescue operations as the robot can move over irregular terrain of collapsed and destroyed buildings.

In our living environment, the most difficult artificial obstacles to move over are stairs. There have been many studies to improve the ability to traverse stairs using legged-type, crawler-type and wheeled-type robots that have special shapes. Among these mobile robots, crawler-type and wheeled-type robots are easier to control and so there are many examples, including crawlers with attached grousers (Hirose et al. 1989; Hirose et al., 1990; Hirose et al., 1992), crawlers for rescue operations (Takayama et al., 2000; Granosik et al., 2005; Liu et al., 2005; Arai et al., 2006; Tanaka et al., 2006; Miyanaka et al., 2007), wheels with coil springs (Hirose et al., 1991), special tires (Uchida et al., 1999; Uchida et al., 2000), and legs that rotate along wheels (Taguchi et al., 1995; Schempf et al., 1999).

In the present research, our goal is to design a practical vehicle to obtain high terrain adaptability and mobility in the human living environment, especially to traverse stairs or steps. To acquire reliable mobility, we developed a new crawler that can obtain a high grip force not by grousers hooking the stairs, but by the deformation of the face material that touches the edges of the stairs. Experimental results revealed that the characteristics of the material that composes the face of the crawler belt affect the grip force. In the present research, a tracked climber vehicle with powder-filled belts carrying heavy loads is proposed and developed, and the efficiency and practical applicability of the proposed tracked climber vehicle are verified.

4. Comparison of a Crawler with Rigid Grousers and with Soft Deformation Belts

A previous crawler was equipped with grousers in order to obtain a certain grip force on stairs. Grousers work very well when the crawler moves over sand or mud, and such crawlers can support heavy loads. However, in the case of traversing stairs or steps, such crawlers have a number of disadvantages, as described below.

1. The intervals of the grousers and the steps do not generally coincide. Thus, the crawler is held by only one grouser on one crawler belt, as shown in Figure 12. Carrying heavy loads with this gripping grouser causes the vehicle to vibrate and may destroy the stair edge. Gripping force is lost easily after the stair edge is destroyed or one of the grousers becomes caught on an obstacle on the stairs. These phenomena reduce the vehicle’s stability and safety, and thus these should be avoided.

2. Slippage may occur when the crawler descends the stairs. When ascending the stairs, the crawler belt simply spins until the grouser touches the step. However, when descending the stairs, the crawler moves forward, down the stairs, even when the grousers do not catch a step.
3. A grouser that has caught a step moves backward as the crawler moves forward up the stairs, as shown in Figure 13. The grouser leaves the step when the grouser comes to the end of crawler. In this situation, other grousers may not necessarily be touching the next step. Therefore, the crawler may slip down or spin off the belt until another grouser catches the next step.
4. If it does not climb the stairs in a straight path, the crawler may not obtain sufficient grip force because the grousers, which have a wide structure for easy attachment to the crawler belt, would touch the stair edges at an angle. This would hamper the mobility of the crawler when adjusting the trajectory to the right or to the left when climbing stairs.

These disadvantages can be partially solved by arranging the grousers in shorter intervals. However, as shown in Figure 14, grousers arranged in short intervals do not have large support areas. Furthermore, if the intervals between the grousers become shorter, the ability to climb stairs in non-straight trajectories becomes worse, thus increasing the consequences of the fourth disadvantage.

As shown in Figure 15, deforming the crawler belt adaptively to the stairs to obtain a grip force from all of the steps appears to be an effective method by which to address these disadvantages. Supporting the crawler at several points prevents slippage accidents caused by the lack of stair edges or by an obstacle becoming caught between the stairs and the crawler belt. In addition, by changing the support points when the vehicle is moving also avoids a freely spinning belt. The required grip force at each grip point is far smaller than in the case of only one grip point.

To obtain a grip force from each step as described above, a rubber material with a large friction coefficient can be easily attached to the face of the crawler belt. However, this method is not necessarily practical for versatile application. For example, outdoor stairs with rounded edges, stairs with metallic edges that have a low coefficient of friction, oily stairs in factories or stairs covered by fallen leaves or dust may cause slippage. In such environments, a greater grip force may be obtained by making a ditch on the belt at the edges of the steps so that the crawler belt will match the stair edge shape and the effectiveness of the crawler will not depend on the friction at the face of the belt. Aligning materials with soft deformation characteristics to the face of the crawler belt is considered to be an effective and practical method by which to achieve these characteristics.

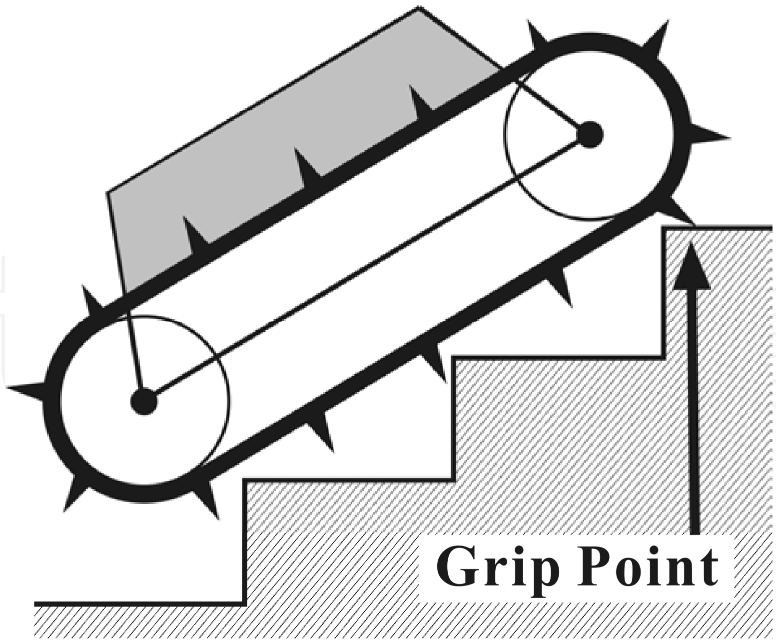


Fig. 12. Grouser-attached stair-climbing crawler

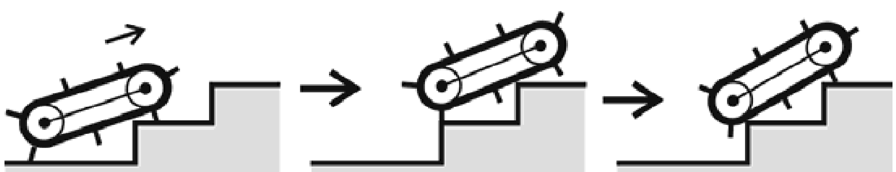


Fig. 13. Slippage problem of the grouser-attached stair-climbing crawler

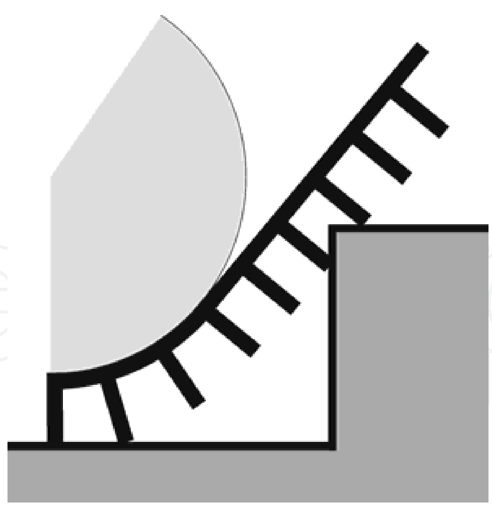


Fig. 14. Problem of short distance between grousers

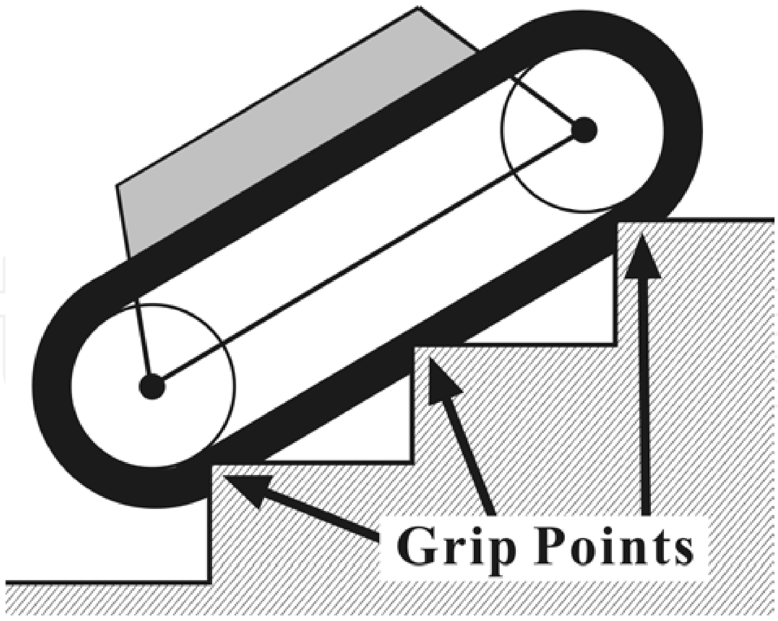


Fig. 15. New concept of stair-climbing crawler

5. Blocks Filled with Powder and Comparison of the Characteristics of Materials

5.1 Blocks Filled with Powder

Usually, rubber or a urethane sponge (which have soft deformation characteristics) are used as the track material, as mentioned earlier. However, as shown in Figure 16, we have developed special blocks that attach to the crawler belt and rely on the deformation characteristics of fluids. Tubes with durability and flexibility are filled with powder and the edges of the tubes are bent for the purpose of attachment to the crawler belt. In the present study, flour is used as the powder. Sand was also found to be an effective powder. A fire hose is used as the tube material. The hose is turned inside out so that the cloth side faces inward and the resinous side faces outward. There is room for improvement in the durability and water-resistance of these materials.

Next, a comparison of the characteristics between the developed blocks filled with powder and the previous soft materials will be performed. Furthermore, the suitability of materials for the crawler belt for a stair-climbing crawler is examined.

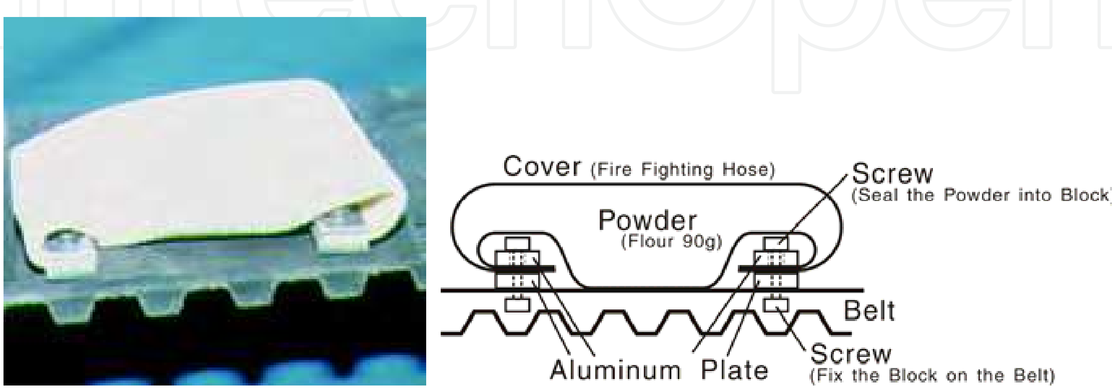


Fig. 16. Powder-filled block

5.2 Friction Characteristics of each Block

For measuring the characteristics of the face material used for the crawler belt of a stair-climbing crawler, the experimental device shown in Figure 17 was prepared. An aluminum block acts as a stair edge and presses against the measured soft material, applying a sideways force. First, the relationship between vertical force and vertical deformation when the experimental edge is pressed was measured. Next, for measuring the grip ability against the stair edge, vertical and horizontal forces were measured when slight slippage occurred due to a horizontal force during vertical loading. The equivalent frictional coefficient for each vertical loading is calculated as:

$$\text{Equivalent Friction coefficient} = \frac{\text{Horizontal Load (Grip Force)}}{\text{Vertical Load}} \tag{1}$$

The equivalent frictional coefficient is measured for cases of increasing vertical load and decreasing vertical load from the maximum load because of the hysteresis characteristics of the materials. The measured materials were the newly developed powder-filled block, a urethane rubber block with approximately the same vertical deformation, a urethane rubber block in the tube used in the newly developed powder-filled block, and the tube itself. The size of these experimental materials is the same as that of the powder-filled block, as shown in Figure 5 (90L × 50W × 30H, 100 g). In order to examine the change in the characteristics with the diameter of the powder, the blocks were filled with aluminum balls of 3 mm in diameter and plastic balls of 6 mm in diameter.

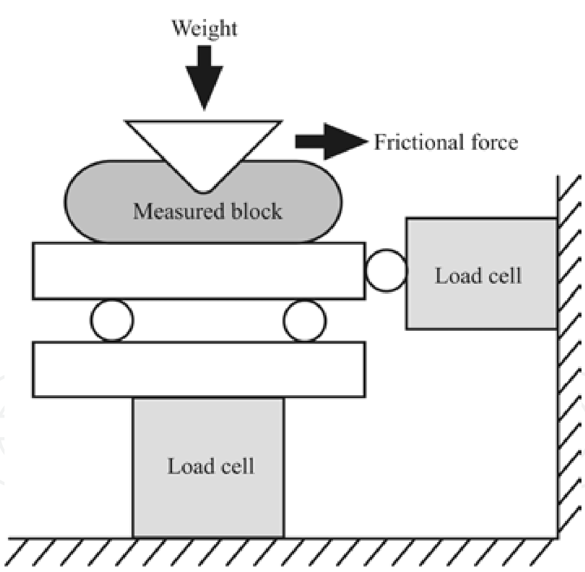


Fig. 17. Experimental system

5.3 Measurement Results of Deformation

First, the results of a comparison of the deformation between the urethane rubber block and the powder-filled block are shown in Figure 18. The same deformation characteristics are observed with an increasing vertical load. However, with a decreasing vertical load, the powder-filled blocks retain their previous deformation, whereas the urethane rubber blocks do not. Next, the results of a comparison of the deformation for different types of powder are shown in Figure 19. This comparison includes the powder-filled block, and the blocks contained 3 mm aluminum balls and 6 mm plastic balls. The results show that the blocks had approximately the same characteristics in each case of increasing and decreasing loads, whereas the maximum deformations differed. Moreover, the results reveal that the blocks have large hysteresis characteristics in common.

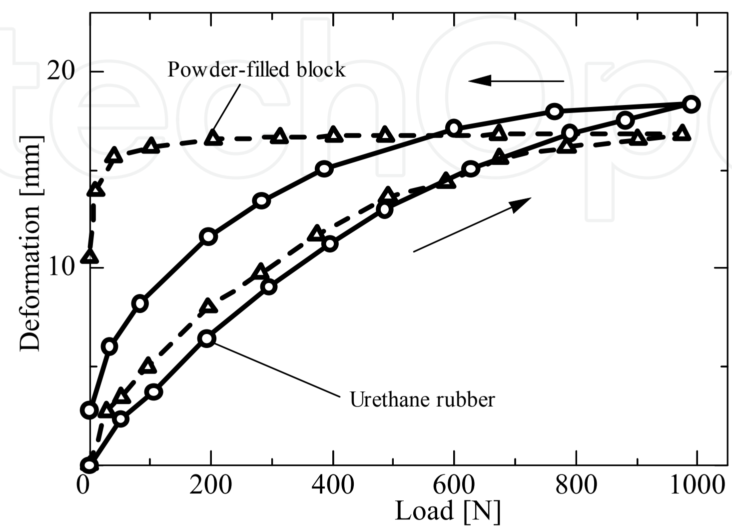


Fig. 18. Characteristics of block deformations

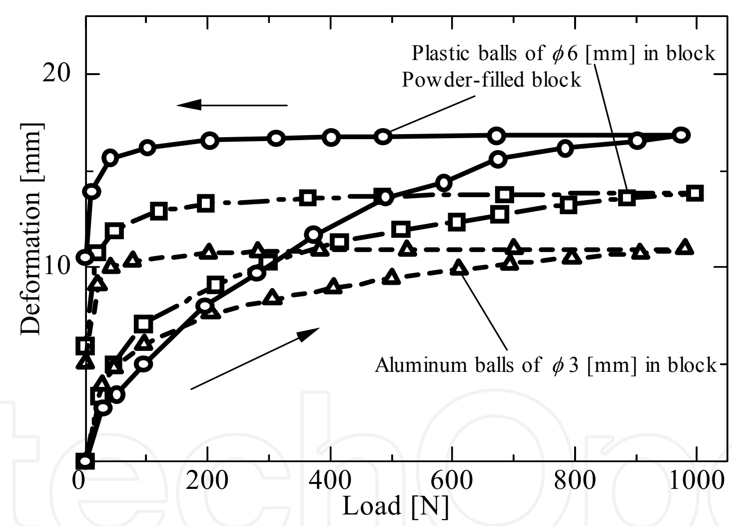


Fig. 19. Comparison of deformation with inner particle size

5.4 Results of Equivalent Frictional Coefficient

Figure 20 shows the results of the measurements of the equivalent frictional coefficient for the four types of blocks: urethane rubber block, the tube itself, urethane rubber in the tube and the powder-filled block. The results show that the equivalent frictional coefficient of the powder-filled blocks becomes much higher than the equivalent frictional coefficients of the other blocks. A very high equivalent frictional coefficient was obtained in the case of a weight reduction. This appears to depend on the hysteresis characteristics of the powder-filled block, because the block maintains its deformation after load reduction. This characteristic benefits the crawler because larger friction forces can be obtained from the middle of the crawler belt where the low-pressure area is located, even while climbing stairs, as shown in Figure 21. The total friction force of the blocks is expressed as the sum of the adhesive friction force, which depends on the face characteristics of the material and the friction force due to deformation that occurs during motion. The adhesive friction force depends only on the facing material, and the friction force due to deformation depends only on the inner materials. For example, friction forces due to deformation are the same between the urethane rubber block and the urethane rubber blocks inside the tube. The difference is the adhesive friction force due to the face material of the tube. Moreover, the friction force due to deformation of the inner powder can be calculated as the total friction force of the powder-filled blocks minus the friction of the tube, which is adhesive friction. Thus, the ratio of adhesive friction to the friction due to deformation for a specific loading can be expressed as shown in Figure 22. Almost all of the friction of the powder-filled blocks is attributed to the deformation. Therefore, it appears that a stable grip force can be always obtained, despite the grounding state of the environment. However, the friction force of the rubber blocks depends on the friction at the surface, and this is not desirable.

This result also shows that the crawler with the powder-filled belt has a relatively smaller friction force on flat surfaces, such as asphalt or concrete. When the crawler moves over a flat surface, the powder-filled blocks deform little because the ground presses equally towards the powder-filled blocks; little energy is lost by rolling resistance which depends on the hysteresis loss. Therefore, the crawler with powder-filled blocks also has better mobility for tasks on flat surfaces such as curving or pivot turning (by relatively small surface friction) and for climbing stairs (by large frictional force due to deformation).

Next, the same experiments were performed in order to compare the effects of the size of particles and materials. The results are shown in Figure 22, which compares the 3 mm diameter aluminum balls with 6 mm plastic balls. The large equivalent frictional coefficient and hysteresis characteristics were approximately the same. Therefore, variations in the inner material and size do not play a very important role in defining the friction force generated by the block. Flour, however, becomes harder and stiff and does not change its form once it has been subjected to loads greater than 2500 N. Thus, the size and the materials used for the inner powder should be decided according to the intended environments and the load carried. Otherwise, the particles can be destroyed and the block will no longer be able to change its form.

After several experiments, the following results were obtained.

1. Sand can generate large friction forces but is heavy.
2. The 3 mm diameter aluminum ball can also can generate large friction forces, but is also heavy (150 g) and very expensive.
3. Plastic balls or rice, which is fragile, cannot maintain their frictional performance because the characteristics of the particles change as they break into smaller particles.
4. The sack should be composed of a non-expandable material.

Based on these considerations, we have developed a stair climber with powder-filled blocks filled with flour.

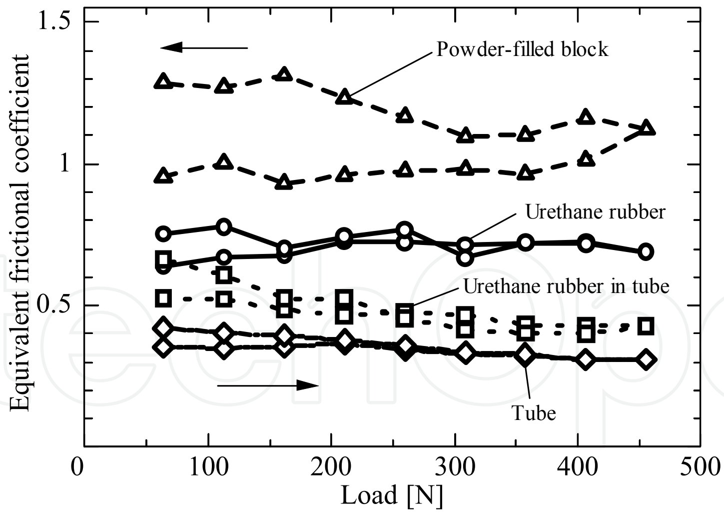


Fig. 20. Characteristics of equivalent coefficient

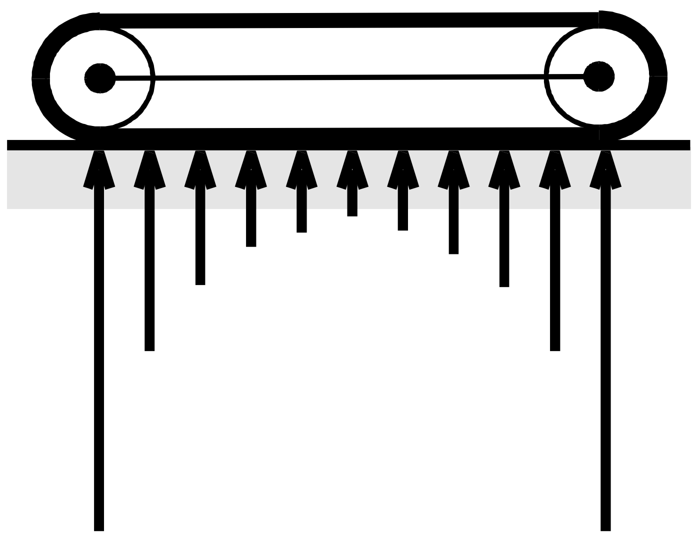


Fig. 21. Grounding pressure distribution

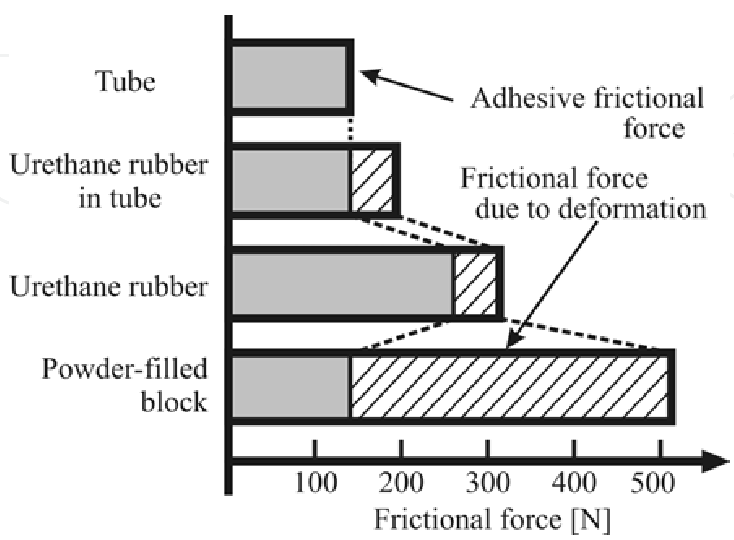


Fig. 22. Comparison of total friction (at 455 N loading)

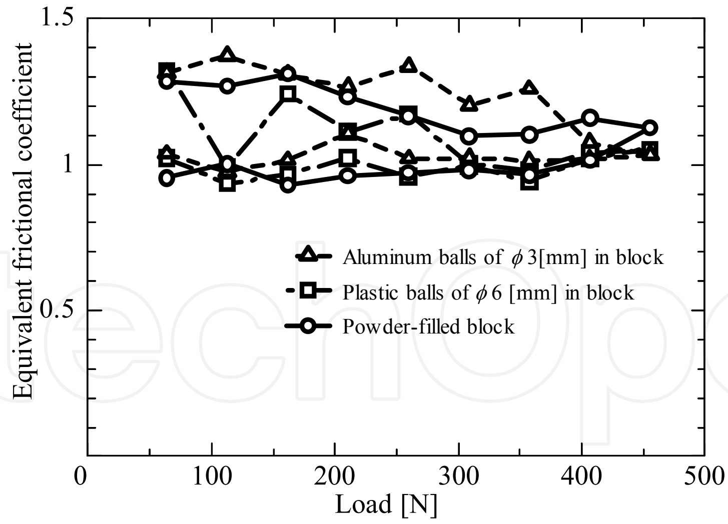


Fig. 23. Comparison of equivalent coefficients of friction with inner particle size

6. Design of Crawler Vehicle

To verify the advantages of using powder-filled blocks when considering stair-climbing safety and reliability, the stair-climbing crawler (Yoneda et al., 2001) as shown in Figure 24 was developed. The climber has a total length of 1180 mm, a width of 830 mm and a weight of 65 kg, including the batteries. This vehicle has a maximum speed of 500 mm s^{-1} and the batteries have a lifespan of 45 min.

To design the deformable powder-filled tracks a total of 112 powder-filled blocks, which were tested from the previous chapter, were attached to each crawler belt (Figure 25). Twenty-eight powder-filled blocks are aligned in two rows per belt. The blocks on the left and right rows are longitudinally shifted by one-half pitch so as to prevent their gaps from coinciding. Thus, the edge of the stair cannot fit within a gap of the block. We can therefore omit the effect of gripping by gaps and check the actual grip performance of powder deformation.

This crawler is also equipped with the belt tension mechanism shown in Figure 26, which was developed to achieve equally distributed grounding pressure. This crawler is also equipped with the active swing idler mechanism shown in Figure 27. This idler is located at the same height as the front and rear main idlers in order to achieve grounding pressure at the middle area of crawler belt, as shown in Figure 28(a). When the crawler approaches the top of the stairs, the swing arm moves and pulls the idler up, bending the crawler belt as shown in Figure 28(b). This motion prevents the sudden change of the posture of the crawler. When the crawler is required to perform pivot turning, the idler is pushed out and the grounding area becomes small, as shown in Figure 28(c). This motion makes pivot turning easier on high-friction surfaces, such as an asphalt road.

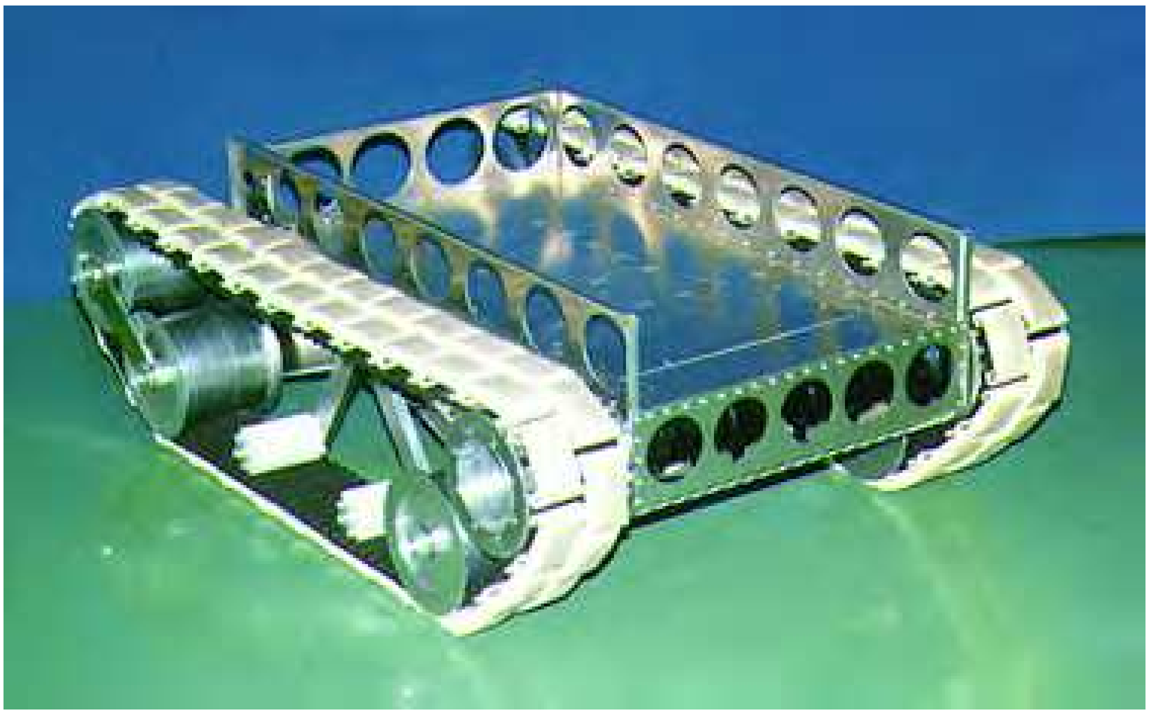


Fig. 24. Developed stair climber with powder-filled belts to which numerous powder-filled blocks are attached

Fig. 25. Alignment of the powder-filled blocks on the belt

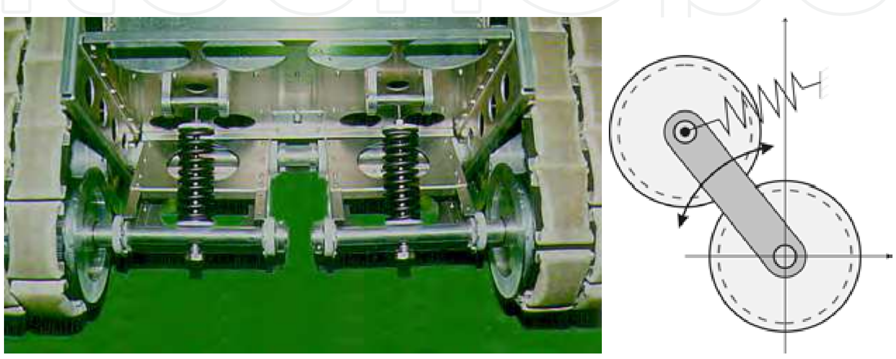


Fig. 26. Belt tension mechanism

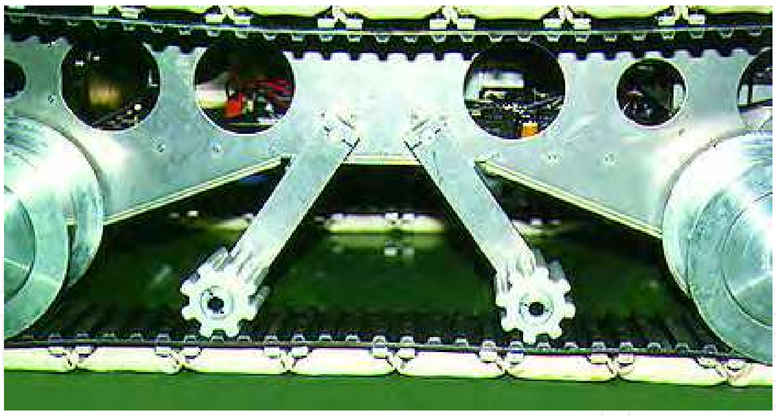


Fig. 27. Active swing idler mechanism

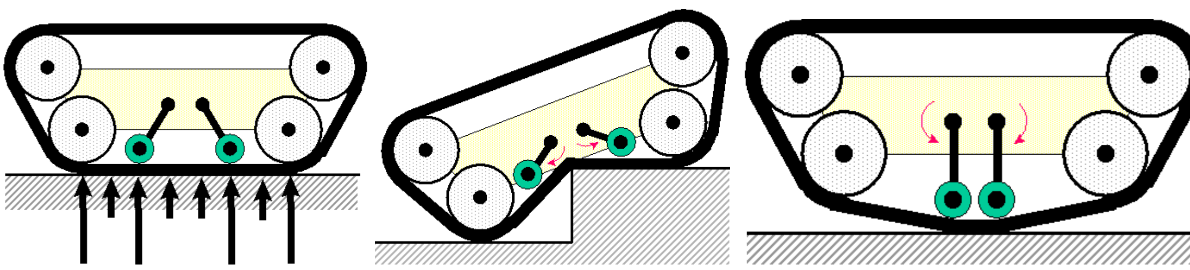


Fig. 28. Three states of the crawler: (a) normal use; (b) when the crawler reaches the top of a stair; and (c) during pivot turning

7. Stair-Climbing Experiment

To verify the abilities of the developed stair-climbing crawler with powder-filled belts, comparison experiments between a crawler with powder-filled belts, a crawler with grouser-attached tracks (Figure 29) and a crawler with urethane rubber blocks (Figure 30) were performed. The stairs used in these experiments have steps of 270 mm in length and 150 mm in height having R2 edges that are sharper than ordinary stairs. All of the crawlers were able to ascend and descend the stairs. In addition the traction forces, which give an indication of the margin of stability and payload, were measured. The results of traction forces are shown in Table 1. It was observed that the developed crawler with powder-filled belts can generate a large traction force that is approximately twice as large as that of the crawler with urethane rubber blocks. The crawler with grouser-attached tracks was able to generate large traction forces when the grousers achieve a good grip on the stair edges. However, as mentioned above, slippage or spinning has been observed when the support point changes. Figure 31 shows the measurement of the pitching angle of the inclination while ascending the stairs. The crawler with grouser-attached tracks generates a larger change in inclination angle than the crawlers with powder-filled belts and urethane rubber blocks.

Furthermore, the crawler with powder-filled belts was able to climb steeper stairs (step length 270 mm, step height 160 mm and edge radius 5 mm), although the crawler with urethane rubber blocks could not ascend because of an insufficient grip force. Moreover, climbing experiments involving the crawlers moving on stairs in non-straight trajectories were performed. Although the crawler with grouser-attached tracks could not ascend the stairs because the grousers could not obtain a sufficient traction from the stair edges, the crawler with powder-filled belts could ascend and descend the stairs stably. In addition, the crawler with powder-filled belts can also adjust its path to the right or to the left stably while ascending and descending stairs. Thus, climbing spiral stairs, which is a difficult task for most conventional stair-climbing vehicles, can be realized. The developed crawler with powder-filled belts can carry the heavy loads, as shown in Figure 32, and the maximum payload capacity is approximately 60 kg when ascending 30 degrees stairs. Furthermore, it was confirmed that the change in the posture becomes smooth at the top of the stairs and easy pivot turning is performed even if the grounding pressure becomes high because of the heavy load on the belt tension mechanism and active swing idler mechanism.

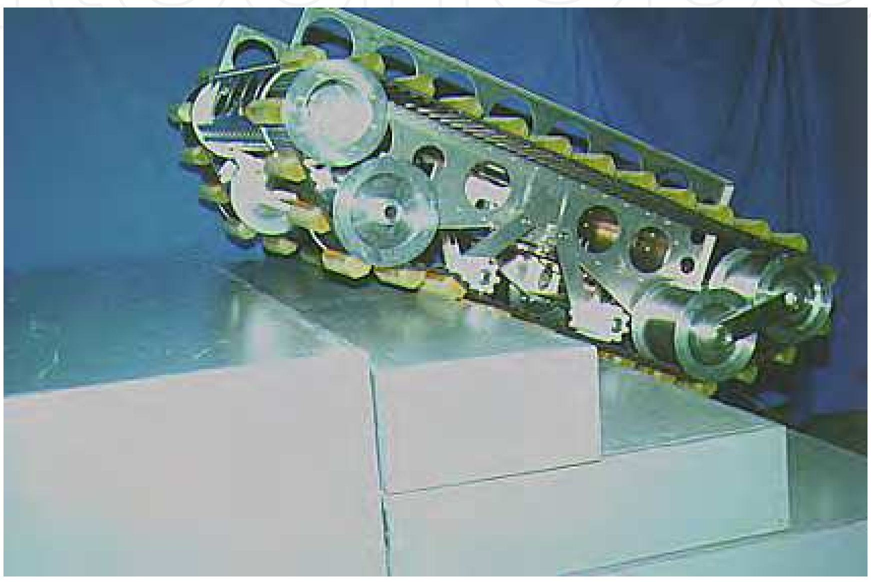
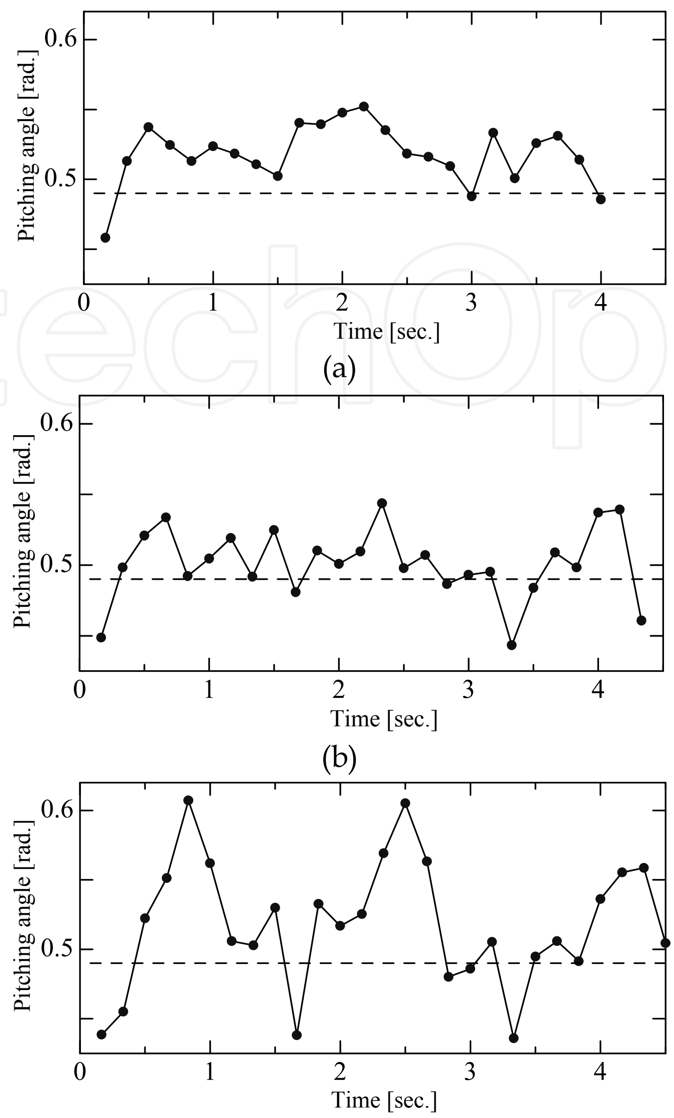


Fig. 29. Crawler with grouser-attached tracks

Fig. 30. Crawler with urethane rubber blocks



(a)

(b)

(c)

Fig. 31. Pitch angle variation of stair climbing with (a) powder-filled belts; (b) urethane rubber belts; and (c) grouser-attached tracks.

8. Conclusion

We describe a practical stair-climbing crawler and the mechanisms required to obtain sufficient grip force on the stairs. We developed powder-filled belts, which consists of several powder-filled blocks attached to the surface of the crawler belt, and compared the characteristics between the powder-filled blocks and other conventionally used materials. The results reveal that after the powder-filled belts deform to match the stair edge, the belts become harder and are therefore able to keep their shapes. This hysteresis characteristic of the attached powder-filled blocks is due to the fact that the powder flow generates a large equivalent friction coefficient at the middle area of the crawler belt, where there is a lower grounding pressure area after the pressure has been increased once. This has been verified experimentally.

After these experimental verifications, we used this high-grip climber for practical application in helping to carry heavy baggage. We can use the developed climber under several ground conditions with a variety of frictional conditions, such as asphalt, concrete and carpet. Several types of stairs, such as steep stairs (approximately 50 degrees), spiral stairs, narrow stairs, round edged stairs and wet stairs, were also ascended and descended successfully. Under these difficult conditions, the powder-filled belt and composed blocks always deliver sufficient grip force without breaking down. These findings reveal that the newly developed stair-climbing crawler with powder-filled belts has sufficient durability for practical application.

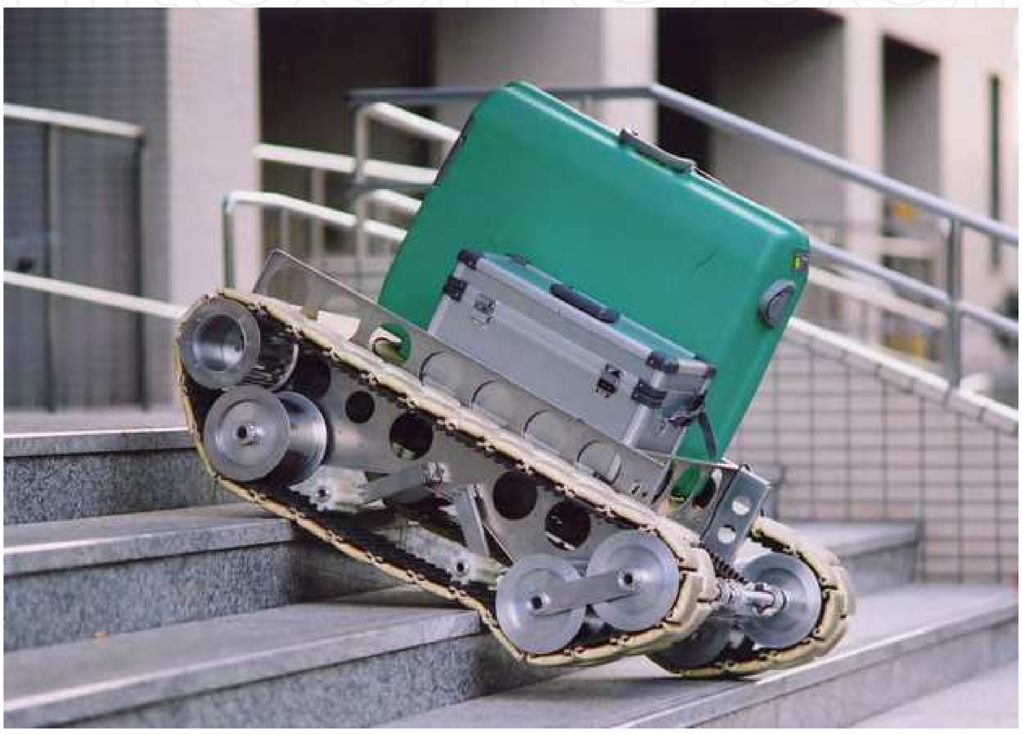


Fig. 32. Ascending stairs while carrying heavy objects

Powder-filled belt	441
Urethane rubber belt	226
Grouser-attached tracks	> 490

Table 1. Results of traction force experiments (N).

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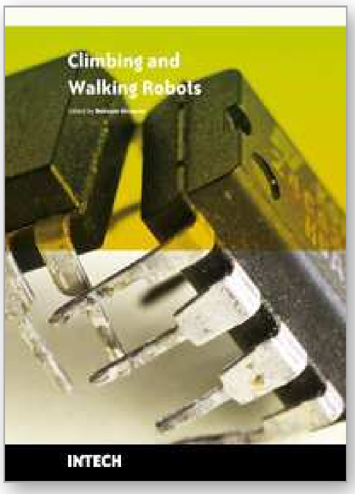

Climbing and Walking Robots

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Nowadays robotics is one of the most dynamic fields of scientific researches. The shift of robotics researches from manufacturing to services applications is clear. During the last decades interest in studying climbing and walking robots has been increased. This increasing interest has been in many areas that most important ones of them are: mechanics, electronics, medical engineering, cybernetics, controls, and computers. Today's climbing and walking robots are a combination of manipulative, perceptive, communicative, and cognitive abilities and they are capable of performing many tasks in industrial and non- industrial environments. Surveillance, planetary exploration, emergence rescue operations, reconnaissance, petrochemical applications, construction, entertainment, personal services, intervention in severe environments, transportation, medical and etc are some applications from a very diverse application fields of climbing and walking robots. By great progress in this area of robotics it is anticipated that next generation climbing and walking robots will enhance lives and will change the way the human works, thinks and makes decisions. This book presents the state of the art achievments, recent developments, applications and future challenges of climbing and walking robots. These are presented in 24 chapters by authors throughtot the world The book serves as a reference especially for the researchers who are interested in mobile robots. It also is useful for industrial engineers and graduate students in advanced study.